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Measurement of Small Mechanical Vibrations of Brain Tissue Exposed to Extremely-Low-Frequency Electric Fields

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16. ABSTRACT

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Measurement of Small Mechanical Vibrations of Brain Tissue Exposed to Extremely-Low-Frequency Electric Fields

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Electromagnetic fields can interact with biological tissue both electrically and mechanically. This study investigated the mechanical interaction between brain tissue and an extremely-low-frequency (ELF) electric field by measuring the resultant vibrational amplitude. The exposure cell is a section of X-band waveguide that was modified by the addition of a center conductor to form a small TEM cell within the waveguide structure. The ELF signal is applied to the center conductor of the TEM cell. The applied ELF electric field generates an electrostrictive force on the surface of the brain tissue. This force causes the tissue to vibrate at a frequency equal to twice the frequency of the applied sinusoidal signal. An X-band signal is fed through the waveguide, scattered by the vibrating sample, and detected by a phase-sensitive receiver. Using a time-averaging spectrum analyzer, a vibration sensitivity of approximately 0.2 nm_{p-p} can be achieved. The amplitude of the brain tissue vibrational response is constant for vibrational frequencies below 50 Hz; between 50 and 200 Hz resonant phenomena were observed; and above 200 Hz the amplitude fall-off is rapid.

Key words: mechanical vibration, electrostrictive force, electric field, brain tissue, extremely low frequencies

INTRODUCTION

In order to understand and explain the mechanisms of interaction between biological systems and electromagnetic fields, it is useful to examine all the forces that may be applied to the tissue as a consequence of exposure. Electromagnetic fields can interact with biological tissue to produce mechanical as well as electrical effects. While there have been many theoretical and experimental investigations of the electrical interaction, few studies have dealt with mechanical phenomena. One possible exception to this statement, however, has been studies involving the microwave hearing effect [Chou et al, 1982; see review in Elder and Cahill, 1984]. It is generally

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accepted that the perception of microwave pulses is a result of a pressure wave being created in the head due to a rapid heating of the tissue by the electromagnetic pulses.

Another pressure that can be produced in tissues exposed to electromagnetic energy is called an electrostrictive force. The magnitude of this force, however, is unknown for biological materials. To fill this void, this study investigates the electrostrictive interaction between brain tissue and an extremely-low-frequency (ELF) electric field by measuri[illegible] the resultant vibrational amplitude of the tissue.

The vibrational amplitude measurements were conducted in a microwave X-band waveguide that was modified by the addition of a center conductor to form a small TEM cell within the waveguide structure. An ELF signal is applied to the center conductor of the TEM cell. An X-band signal is fed through the waveguide, scattered by the vibrating sample, and detected by a sideband heterodyne receiver. To enhance the receiver sensitivity, a time-averaging spectrum analyzer was also utilized.

ELECTROSTRICTIVE FORCES AND DISPLACEMENT

For an object, specified by volume V and surface S, containing a charge distribution and a current distribution, the total force acting on the object is given by [Stratton, 1941]

$$\bar{F} = \int_S [\epsilon \bar{E}(\bar{E}\cdot\bar{n}) - \frac{\epsilon}{2}\bar{E}^2\bar{n}]ds + \int_S [\mu \bar{H}(\bar{H}\cdot\bar{n}) - \frac{\mu}{2}\bar{H}^2\bar{n}]ds - \frac{1}{c^2}\int_V \frac{\partial}{\partial t}(\bar{E}X\bar{H})dv \quad (1)$$

The first two integrals are surface integrals and the last one is a volume integral. The quantity $\bar{n}$ is an outward unit vector normal to the surface, S. For all practical purposes, the last term is of no importance because the factor $1/c^2$ makes it negligible with respect to the other terms. Likewise, for biological tissues with $\mu \approx \mu_0$ the second term is essentially equal to zero. Thus, in what follows we will investigate the magnitude of the force produced by the first term. For static or quasistatic fields this force is called an electrostrictive force.

Because the exposure situation is an ELF electric field, the fields on the surface of the tissue will terminate predominantly normal to the dielectric surface. This means that only the normal electric fields have to be considered in the evaluation of the first term of equation 1. Therefore, the pressure or force per unit area acting on the surface is [Joines and Wilson, 1981]

$$\bar{P} = -(1/2)\epsilon_o[(\epsilon_o/\epsilon) - 1]\, E^2\, \bar{n} \quad (2)$$

where ϵ is the permittivity associated with the object, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m, and E is the magnitude of the normal electric field on the outside surface of the object. Further, because at low frequencies the permittivity of brain tissue satisfies the inequality $\epsilon >> \epsilon_0$, it is possible to approximate equation 2 by the following

$$\bar{P} = (1/2)\, \epsilon_o\, E^2\, \bar{n} \quad (3)$$

It is interesting to observe that the direction of the force does not depend on the polarity of the electric field and also that the force is always directed from the region with the higher permittivity to the region with the lower permittivity. Thus, for an object located in free space the electrostrictive force will always tend to stretch the object in the direction of the force. Of course, the object will also contract at right angles to the stretch. Figure 1 illustrates this situation, where the stretch length is denoted by ΔW and the change in lateral width (contraction) is represented by ΔL.

Because the electrostrictive forces are small, the material should obey Hooke's law, that is

$$\Delta W = (PW)/Y \tag{4}$$

where Y is Young's modulus. The contraction due to the stretch is given by

$$\Delta L = (P\sigma L)/Y \tag{5}$$

where σ is Poisson's ratio and P is the magnitude of the surface pressure. Equations 4 and 5 are adequate to describe the stretch or contraction (assuming homogeneous and isotropic material) amplitudes under static or quasistatic conditions. In other words, the equations are valid if the object is acted upon by a force whose frequency is below the natural resonant frequencies of the object. When the frequency of the driving force is raised, the object may exhibit a series of resonant displacements whose amplitudes may be larger than the quasistatic case. For very high frequencies, the vibration amplitude will approach zero as the inertial forces become dominant.

In general, however, the vibrational motion associated with the object subjected to a quasistatic electric field can be put in the form

$$x(t) = K\,E^2(t) \tag{6}$$

where x(t) can represent either the stretch or contraction of the tissue and K is a constant. Notice that the vibration amplitude is a nonlinear function of the electric field. A nonlinear response produces several effects: rectification, generation of harmonics, and modulation. For sinusoidal fields, if $E(t) = E_0 \cos \omega_0 t$, it is easy to show that

$$x(t) = (E_0^2 K)/2 - (E_0^2 K)/2 \cos 2\omega_0 t. \tag{7}$$

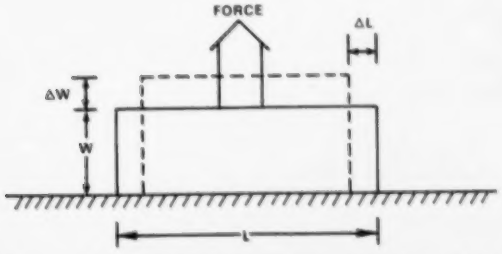

Fig. 1. Change in shape of an object experiencing an electrostrictive force.

Thus, if the object is placed in an alternating electric field, the object experiences a constant strain as well as an alternating strain at twice the frequency (second harmonic) of the applied field. The constant term corresponds to a shift of the average value and thereby produces rectification. The doubling of the vibration frequency relative to the applied frequency has been previously demonstrated in a study concerned with hearing audio frequency electric fields [Sommer and von Gierke, 1964].

MICROWAVE RECEIVER AND EXPOSURE SYSTEM

Sideband Heterodyne Receiver

To investigate quantitatively the electrostrictive-induced vibration in biological tissue requires unique instrumentation because the vibration amplitude will be very small. Although greater sensitivity can in general be achieved with optical techniques, preliminary work with microwave systems indicated a sensitivity capability comparable to all but the most complicated optical systems [Luymes, 1983]. In addition, comparable sensitivity can be obtained at less cost with microwave systems. Therefore, a microwave system with a sideband heterodyne receiver was utilized to make quantitative measurements of the vibrational motion.

Figure 2 illustrates the problem. If the signal transmitted by the microwave source is $V_0 \sin \omega t$ and the object is vibrating according to $x_0 \sin \omega_m t$, then the signal scattered back to the source can be put in the form

$$V_{rec} = \rho V_o \sin(\omega t + \beta_p \sin \omega_m t) \tag{8}$$

where

$$\beta_p \equiv \frac{2\omega x_0}{c}.$$

Also, the constant phase shift term has been dropped and ρ is the ratio of the amplitude of the received signal to the amplitude of the signal at the source. This waveform is a

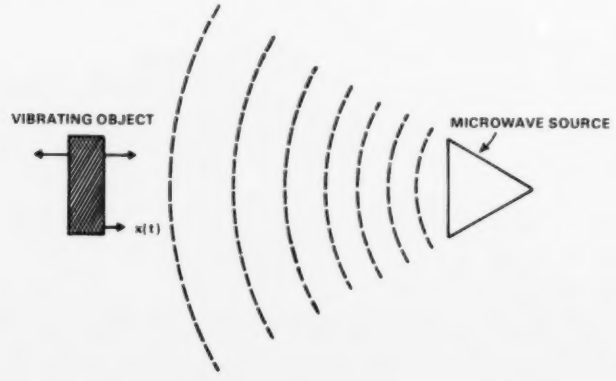

Fig. 2. A vibrating object illuminated by a microwave field.

phase-modulated wave because the phase is varying according to sin $\omega_m t$. The quantity β_p is called the modulation index. After several lines of mathematical derivations that can be found in texts on communication theory, it is possible to show that the received signal can be expressed as

$$V_{rec} \approx \rho V_o[\sin \omega t + (\beta_{p/2})[\sin(\omega+\omega_m)t - \sin(\omega-\omega_m)t]]. \quad (9)$$

Figure 3 illustrates the spectra associated with this signal. From this figure, it is apparent that the received signal contains a spectral line at the frequency of the microwave source and two sidebands at frequencies slightly above and below the carrier frequency.

The information we are after is the vibration amplitude, x_0, which is contained in the phase modulation index, β_p. Forming the ratio of the amplitude of sideband to the carrier amplitude we get

$$\beta_p/2 = \frac{2\pi x_o}{\lambda}. \quad (10)$$

or in dB

$$\beta_p/2|_{dB} = 20 \log_{10}\frac{2\pi x_o}{\lambda} \quad (11)$$

where λ is the wavelength of the microwave signal. Therefore the sideband to carrier ratio depends only on the vibration amplitude for a fixed carrier frequency for the exposure situation depicted in Figure 2.

The exposure situation inside the waveguide exposure cell is somewhat different than a free-space exposure. The phase velocity is larger than the speed of light and the guide wavelength is larger than the free-space wavelength by about 15% for the microwave frequency and waveguide used here. The use of equation 11 with the free-space wavelength inside a waveguide for a flat, linearly vibrating object results in approximately a 1 dB error. This was considered a minor error and therefore equation 11 was used as the basis for all measurements.

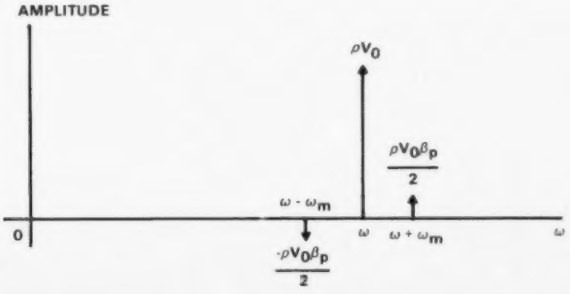

Fig. 3. The spectra associated with the signal received from the scattered field of a vibrating object.

Figure 4 contains a block diagram of the instrumentation used to detect the phase-modulated waveform of the scattered signal. The receiver is best labeled as a sideband heterodyne receiver. A detailed description and characterization of the receiver can be found elsewhere [Ali, 1985], consequently only a brief description is contained here.

A 10.525-GHz, phase-locked source (OSC 1) supplies microwave power for the vibration measurement. Power is routed through a waveguide circulator and to a waveguide switch. In one switch position, microwave power is routed to a calibration cell containing a piezoelectric crystal. Some power is reflected from the crystal back to the receiver while the remaining power is absorbed in a waveguide termination. The piezoelectric crystal is driven by an audio frequency signal generator (OSC 3). The vibration amplitude of the crystal is known and hence a phase-modulated signal with known sideband to carrier power ratio is reflected back to the receiver. This waveguide leg therefore serves as a convenient calibration path. In the second switch position, microwave power is routed toward the sample cell. The sample cell permits the simultaneous exposure of a sample to ELF or amplitude-modulated RF signals and monitoring of the resultant vibration. The signal reflected from either the sample in the exposure (sample) cell or the piezoelectric crystal is directed to the receiver.

The receiver is a sideband heterodyne, phase-sensitive receiver that compares a reference signal derived from the splitter with the phase-modulated signal returned from either the exposure cell or the calibration cell. The signal from the splitter is mixed with a local oscillator at 30 MHz producing sum (10.555 GHz) and difference (10.495 GHz) frequencies. After filtering to remove one of these components, this signal is mixed with the phase-modulated microwave signal to produce a signal whose frequency is in the IF band. Since the bandwidth of the IF amplifiers utilized in the receiver is 10 MHz and since the information bandwidth is less than 1 kHz, there are no long-term drift problems for this receiver. Additionally, a limiting amplifier is used in the receiver to maintain a constant output level over an input range of -70 dBm to -5 dBm. The limiting amplifier permits the calibration of the system to be maintained over a wide range of return signal levels and eliminates AM noise that may be present on the signal. The output of the receiver is an audio frequency signal

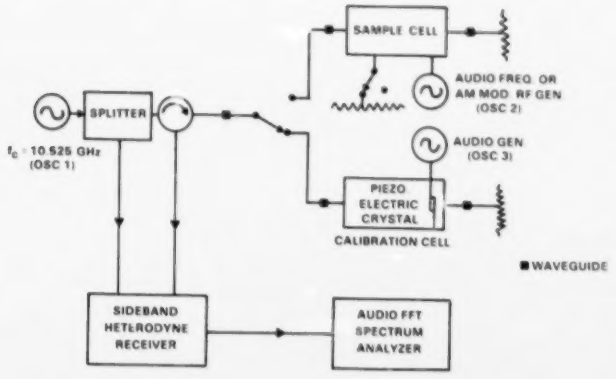

Fig. 4. Block diagram of the microwave monitoring system and sideband heterodyne receiver.

proportional to the phase modulation of the return signal. The output is time averaged and displayed on an audio frequency, FFT type spectrum analyzer (Hewlett-Packard, Model 3582A).

Exposure Cell

A drawing of the exposure cell is contained in Figure 5. It is a modified section of X-band waveguide (WR-112) to which a center conductor has been added to form a small TEM cell within the waveguide structure. The biological sample is placed on the cell, and an ELF signal is applied to the center conductor of the TEM cell. The X-band (10.525 GHz) signal is fed through the waveguide, is scattered by the vibrating sample, and is detected by the sideband heterodyne receiver. While not indicated on the figure, the temperature inside the cell is controlled by a small resistive strip heater on the outside of the cell. In addition, insulating material is placed on the outside surface of the waveguide.

The X-band signal propagates through the waveguide in the TE_{10} mode. This is the lowest order mode that will propagate in WR-112 waveguide, and its cutoff frequency is 5.26 GHz. Since the mode's electric-field lines terminate on the broad walls of the waveguide, each imaginary plane between the narrow walls of the waveguide and parallel to the broad walls is along an equipotential surface. A conductor can be placed along an equipotential surface without disturbing the electric field. Therefore the center conductor of the TEM cell only minimally perturbs the field of the X-band signal. This was demonstrated by measuring the voltage standing wave ratio (VSWR) of the empty exposure cell with one end of the waveguide terminated with a waveguide load. The measured VSWR was 1.06, which means that less than 0.1% of the incident X-band signal is scattered back to the receiver.

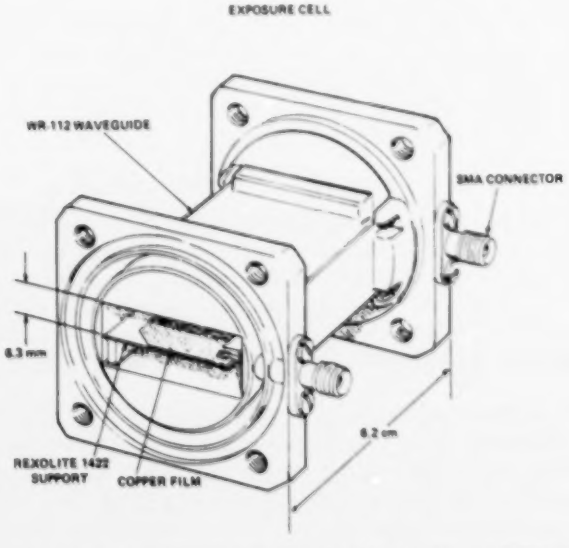

Fig. 5. Drawing of the modified section of X-band waveguide showing the TEM cell utilized for exposing tissue samples.

The TEM cell's aspect ratio is fixed by the dimensions of the WR-112 waveguide: The value is 2.257. The ratio of the center conductor width to the waveguide longest cross-sectional dimension is 0.62. For these values, the TEM cell has a cutoff frequency of 5.26 GHz [Weil et al, 1981]. Therefore to expose the biological sample in the cell to TEM mode fields requires that the frequency of the signal applied to the cell must be kept below this value.

VIBRATIONAL MEASUREMENT

To isolate the instrumentation from mechanical vibrations of the floor, the entire microwave monitoring system was placed on a conventional marble balance table that had air cushions supporting the table top. The table was located on a concrete slab foundation.

Receiver Calibration

As mentioned above, receiver calibration is obtained by measuring the resultant signal from a piezoelectric crystal vibrating at a known amplitude. For this measurement, a piezoelectric crystal (Wilcoxon Research, Rockville, MD, Model PZT5H) was placed in the center of the calibration cell as shown in Figure 4. Wires were soldered to each side of the crystal and routed to a coaxial connector mounted on an X-band waveguide flange. The wires were positioned perpendicular to the X-band field to minimize scattering from the wires. When the crystal is excited by a 4 Vp-p sine wave signal, the crystal will vibrate at the excitation frequency with an amplitude of 2.36 nm_{p-p}. This yields a sideband to carrier ratio (equation 11) of -131.7 dB.

It was found that the receiver sideband to carrier ratio values agreed with the crystal vibrational amplitude as specified by the manufacturer to within 5 dB over a 40 dB range of input power levels. Consequently all measured values of sideband to carrier ratio were corrected by 5 dB for the brain samples. However, the return loss of the exposure cell compared to that of the sample does limit the useful dynamic range of the system: The signal returned by the sample must be larger than the signal returned by the empty exposure cell [Ali, 1985].

Brain Sample

The biological samples utilized in this study were brain tissue obtained from 1–7-day-old chicks (*Gallus domesticus*). The chick forebrains were removed and separated along the midline. The pia matter remained on the uncut portions of each brain half. After removal, the brain halves were placed in a buffer medium that was composed of 155 mM NaCl, 5.6 mM KCl, 2.16 mM $CaCl_2$, 2.4 mM $NaHCO_3$, and 11.1 mM glucose. Each brain half was approximately 1 cm long, 0.8 cm wide, and 0.6 cm thick.

The brain halves were exposed in the TEM cell (Fig. 5) to ELF electric fields. Because only electric fields were utilized in the exposure of the tissue, the cell was not terminated in 50 Ω but was left unterminated (open circuit condition). For this type of operation the TEM cell functions as a parallel-plate capacitor, and the exposure situation can be approximated by the situation depicted in Figure 6. In this figure the bottom plate of the capacitor represents the waveguide wall, and the upper plate is the center conductor of the TEM cell. A potential of V volts applied to the

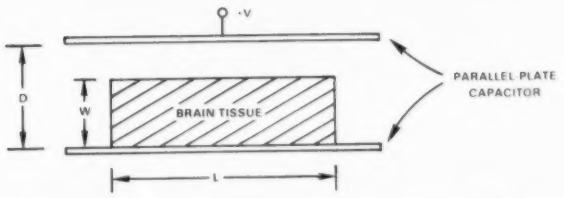

Fig. 6. A parallel-plate capacitor approximation of the TEM cell.

top plate produces an approximate electric field at the surface of the brain tissue given by

$$E = V/(D\text{-}W). \tag{12}$$

To keep the separation distance (D–W) approximately 2 mm, the chick brain half is trimmed on the surface where it was separated from the other half.

For exposure, a chick brain half is removed from the buffer medium, carefully trimmed, and placed within the cell with the disturbed (cut) surface facing downward and with its longest dimension oriented transverse to the waveguide. The undisturbed surface faces upward. The temperature inside the cell is maintained at 37 °C. A 270 V_{p-p} sinusoidal signal is applied to the center plate of the exposure cell (OSC 2, Fig. 4); this signal produces an approximate electric field of 1350 V_{p-p}/cm (Equation 12 with D–W = 2 mm) on the surface of the brain tissue. Further, from equation 3 a pressure of about 0.8 dyn_{p-p}/cm^2 can be expected on the top surface of the brain.

Figure 7 contains a typical spectrum analyzer (HP, model 3582A) trace showing the vibrational signal when the exposure frequency was 45 Hz and the signal was time averaged using 64 samples. As explained earlier (equation 7), the tissue vibrates at twice the frequency of the applied sinusoidal signal, or for this case at 90 Hz. The single sideband to carrier ratio of −117 dB corresponds to a vibrational amplitude of 13 nm_{p-p} (equation 11). It should be noted that the microwave monitoring system measures the contraction length because this motion is associated with the surface of the brain tissue that is essentially perpendicular to the direction of propagation of the incident signal (see Fig. 2). Consequently, this surface scatters more energy back to the receiver than the top surface. Also visible in the spectrum analyzer output are power line noise at 60 Hz and its harmonic at 120 Hz. The receiver 1/f noise restricts vibrational frequency measurements to frequencies above 10 Hz.

Typical results for the vibrational amplitude versus frequency are shown by the curves in Figure 8. A different chick brain half was utilized for each curve. The temperature inside the exposure cell was 37 °C and 30–45 min are required to make the measurements for each curve. While each response is somewhat different, overall similarities are apparent. For example, each response contains a flat portion, and each falls off rapidly above approximately 200 Hz. Thus, the tissue behaves like a low-pass mechanical filter. They all also possess what appears to be a resonant response whose peak amplitude occurs around 100–150 Hz. Note that this response peak is very pronounced for one chick brain and almost nonexistent for another. Further, a resonant-like response at 450 Hz is displayed by one brain half. The variation in vibrational amplitude from curve-to-curve over the flatter portion of the curves is most likely a result of slightly different separation distances from the top

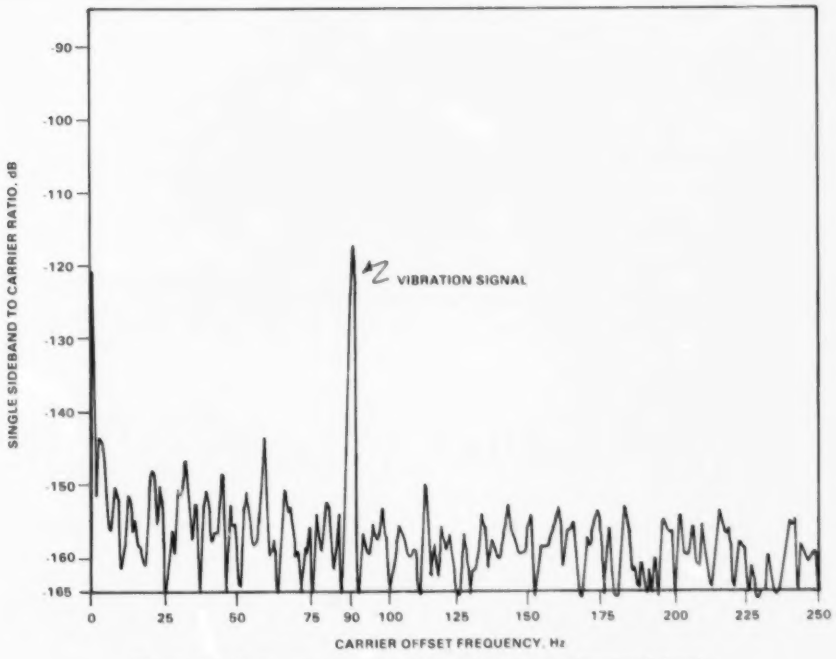

Fig. 7. A typical spectrum analyzer trace showing the vibrational signal.

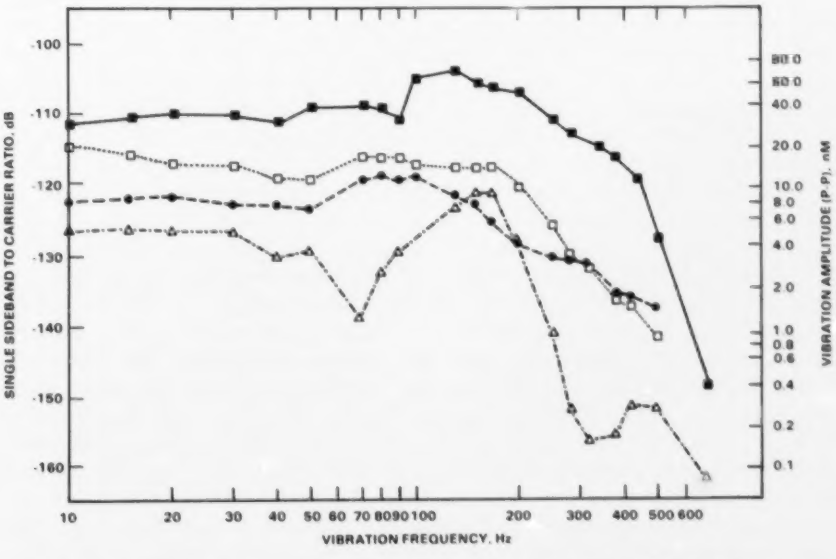

Fig. 8. Vibrational response profiles versus frequency for different chick brain halves.

surface of the tissue to the exposure cell plate (Fig. 6). From equation 12 is readily apparent that minor changes in the separation distance (D–W) greatly affect the electric field strength on the surface of the sample.

DISCUSSION

In this study we measured the mechanical vibrations produced by an electrostrictive force acting on brain tissue. It was found that the tissue vibrated at twice the frequency of the applied sinusoidal electric field. The amplitude of this response is constant for vibrational frequencies below approximately 50 Hz; the magnitude of the response was somewhat different for each brain sample with values between 5 and 34 nm_{p-p} for an applied 270 V_{p-p} sinusoidal signal. Over the frequency range of 50–200 Hz resonant-like phenomena were observed. Above 200 Hz the amplitude fall-off is rapid.

Over the constant portion of the response profile, the stretch and contraction amplitudes can be predicted reasonably well by equations 4 and 5. To utilize these expressions, however, requires knowledge of the elastic parameters of the brain as specified by Young's modulus and Poisson's ratio. Therefore, these parameters were measured using a simple mechanical apparatus [Ali, 1985]. The measured values were $Y = 9.8 \pm 4.0 \times 10^4$ dyn/cm^2 (N = 8) and $\sigma = 0.44 \pm 0.07$ (N = 9). With these average values substituted into equations 4 and 5 as required, the resultant stretch and contracton amplitudes are 33 nm_{p-p} and 29 nm_{p-p}, respectively, assuming $E = 1350$ V_{p-p}/cm. It is to be remembered that the microwave monitoring system measures the contraction amplitude. Comparison of calculated (29 nm_{p-p}) and measured (5–34 nm_{p-p}) values yield reasonable agreement for the contraction amplitude.

Because of the complicated shape of the chick brain half, analytical analysis for the resonant portion of the response profile is difficult. However, some simple models may be used to determine possibly the type of vibration that is occurring. For example, a uniform bar of length L with one end fixed and the other free yields the following expression for the fundamental resonance frequency associated with free longitudinal vibrations [Timoshenko et al, 1974]

$$f_1 = (1/4L)\sqrt{Y/\rho} \tag{13}$$

where ρ is the mass density. The application of this model to a brain sample with L = 0.4 cm, $Y = 9.8 \times 10^4$ dyn/cm^2, and $\rho = 1$ g/cm^3, yields a resonant frequency of 195 Hz. If the motion at resonance is a transverse vibration, then the fundamental resonance of a bar with one end fixed is given by [Timoshenko et al, 1974]:

$$f_1 = (A/L^{3/2})\sqrt{Y/M} \tag{14}$$

where A is the cross-sectional area and M is the mass of the bar. Applying equation 14 with L = 0.4 cm, $A = 1 \times 0.8 = 0.8$ cm^2, and M = 0.2 g yields $f_1 = 2.2$ kHz. Thus, even though these simple models cannot be strictly applied to the brain sample, the results indicate that resonant vibration is longitudinal and not transverse. Further work will be directed toward unraveling the uncertainty regarding this apparent resonant interaction.

Finally, it is interesting to speculate on a potential biological implication of mechanically vibrating brain tissue by the application of an ELF electric field. For example, it has been reported [Bawin and Adey, 1976; Blackman et al, 1982] that ELF electromagnetic fields can alter the association of calcium ions with chick forebrain tissue in vitro. Additional studies [Adey et al., 1982; Blackman and Wilson, 1983] have further revealed that the outermost 1 mm of brain tissue is most likely implicated in this effect. Thus, it is important to examine all the forces that may be applied to the brain's surface as a consequence of exposure. It is certainly possible to conjecture that a mechanical vibration of the brain's surface might have some influence on the association of calcium ions near the surface. Additional refinements in our procedures and further studies will assist in ascertaining whether this phenomenon plays an important role in calcium-ion efflux.

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